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An In-Depth Analysis of Sustainable Approaches, Conventional Techniques, and Policy Frameworks for Managing Municipal Solid Waste in India

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ABSTRACT

The concentration of India's population has presented the country with various challenges regarding the exponential growth of Municipal Solid Waste (MSW). Globally, the increasing volumes of rubbish have made waste management both environmentally and socially burdensome. The development of safe and renewable resources has assisted in municipal solid waste management. Garbage-to-energy conversion has proven to be an effective method for reducing municipal waste. Biofuel and biogas generation from municipal solid waste are among the renewable energy possibilities within the broader framework of waste management. The review examines sustainable treatment methods for managing municipal waste. It provides an overview of the characteristics and environmental impacts of municipal solid waste. To enhance energy generation, pretreatment approaches have been integrated into waste conversion processes. The review underscores the significance of thermal and biological conversion-based approaches to municipal waste management. Biological treatment technologies have emerged as a significant focal point for energy recovery while maintaining environmental sustainability. Additionally, the review assesses the applicability of various Indian policies for Municipal Solid Waste Management.

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1. INTRODUCTION

The expanding need for affluent lifestyles has significantly impacted the financial system of the nation. India, as one of the fastest-developing countries, has made notable contributions to the world economy. Predictions suggest that the Indian economy will grow by 10% by 2030, potentially elevating living standards. The primary drivers of the global economy also substantially contribute to waste production. The process of industrialization has been spurred by an imbalance in the demand and supply chain (Rao et al., 2019; Mehmood et al., 2021). These activities generate various types of waste, which affect climatic conditions and biological systems. Wastes, categorized as unusable and abandoned substances, can take three forms: fluid, vapor, and solid. Solid wastes, emitted by urban, industrial, and rural areas, are considered a significant environmental burden. There are three main types of solid waste: hazardous, municipal, and industrial wastes (Ren et al., 2021). Municipal solid waste (MSW), generated by municipal and human activities, has had a significant impact on the economy. It has been observed that the generation of MSW has increased dramatically in parallel with population growth rates. Globally, approximately 1.9 billion tonnes of MSW are generated each year, with 30% remaining untreated. Only around 90% of this waste is collected, and merely 20% is processed (Sharma and Jain, 2019; Rafew and Rafizul, 2021).

Food waste, plastics, papers, metals, and other materials constitute municipal solid waste (MSW). MSW production varies depending on factors such as time of day, collection location, region, consumption trends, and economic activities. It results from a variety of human activities. Improper MSW management has several negative consequences for the environment (Istrate et al., 2020; Lu et al., 2020). Exposure of MSW to the local community can lead to the transmission of disease vectors. Leaching of hazardous compounds may occur, emitting foul odors into the ecosystem. Ecologically significant consequences such as climate change, landscape degradation, and contamination of soil and water can result (Cremiato et al., 2018).

MSW management encompasses storage, collection, transportation, processing, and disposal. These processes adhere to criteria related to public health, aesthetics, and economics. Given that a substantial portion of MSW is organic, its treatment significantly impacts energy recovery indirectly. Pretreatment procedures are necessary for effective energy recovery from MSW (Babu et al., 2021; Kumar and Samadder, 2022). Mechanical, chemical, thermal, and biological methods are commonly used for MSW pretreatment. Mechanical treatments, such as shearing, homogenization, and sonication, separate the organic fraction of MSW. Thermal pretreatment aids in pathogen eradication. Chemical pretreatments, such as acid and alkaline treatments, enhance the digestibility of MSW

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components. Biological pretreatment can improve microbial-based hydrolysis (Ahmed et al., 2022; Shah et al., 2019; Mozhiarasi, 2022).

Large-scale burning, trash disposal, and landfilling are examples of traditional MSW remediation techniques. These practices have numerous detrimental effects on the environment and human health. Waste-to-Energy conversion, one of several treatment technologies used for MSW management, can be a viable solution for sustainable energy production while minimizing waste. Using various conversion procedures, a net energy potential of 0.13-0.38 tonnes of oil equivalent per tonne can be obtained. The net energy potential of MSW varies depending on its composition (Munir et al., 2021; Sharma et al., 2020). However, all these traditional systems lack efficient energy recovery. Over time, innovative and environmentally friendly recycling and recovery systems have evolved from basic disposal processes. Proper MSW management approaches, such as sanitary, biological, and thermal methods, are utilized in both developed and developing countries (Roy et al., 2022). Regarding thermochemical MSW treatment, pyrolysis, gasification, and incineration are the most commonly employed techniques. Through the pyrolysis process, liquid biofuel can be produced from municipal solid waste. Pyrolysis gases can be utilized in direct or indirect combustion processes as a heat source (Suresh et al., 2021; Cudjoe and Wang, 2022). When MSW is gasified in an environment with little oxygen, other combustible gases are produced along with syngas. Gas is recovered from burned MSW fractions via incineration, similar to gasification. Fermentation, as a biological technique, has recently emerged as a revolutionary concept for recovering valuable bioproducts and biofuel from MSW. Anaerobic digestion is another biological method in which the organic portions of MSW are degraded and transformed into biogas through a series of biological reactions. Despite these new solutions, municipal solid waste management has become crucial for overall pollution control. In India, several municipal waste management systems for efficient product recovery and waste minimization have been developed (Karthikeyan et al., 2018; Wong et al., 2020; Kheiri et al., 2022). Previous literature has focused on the removal techniques generally involved in municipal solid waste management. There is a lack of studies focusing on pretreatment approaches before the management techniques are implemented.

The current review focuses on sustainable conversion techniques in municipal solid waste management and its application in India. Pretreatment approaches before the conversion processes have been emphasized in this literature review. The qualities and their effects on individuals and the environment have been discussed throughout the process. In this context, the current state of MSW generation in India, along with its pretreatment measures, has been highlighted. Thermal and biological-based sustainable treatment solutions for MSW have been thoroughly detailed. The corresponding MSW management policies in India have also been briefly covered in this review.

2. MUNICIPAL SOLID WASTE

2.1 Characteristics

Municipal solid waste (MSW) is a broad category that includes many different heterogeneous components from urban and residential activities, each with its own composition. The quantity and type of MSW generated vary depending on geography, economic level, culture, and location. In general, there are two types of MSW: inorganics and organic. Glass, ash, and metals are examples of inorganics, whereas organics include paper, wood waste, textiles, and food residues. MSW includes garbage from industries, residents, authorities, farms, and the demolition sector. Based on population growth, paper content ranges from 2.9 to 6.5% (Lu et al., 2017). The majority of MSW generated in India is organic trash (70-75%). This organic component of MSW comprises a higher concentration of hemicellulose, cellulose, and fats and proteins generated from food and other paper wastes. Furthermore, the organic fraction contains a substantial amount of anaerobic microorganisms that can aid in the conversion process. Potassium and phosphorus concentration range from 0.5 to 0.8%, whereas the nitrogen value ranges from 0.5 to 0.7%. The calorific value ranges between 800-1200 kCal/kg. In Indian cities, the C/N ratio for MSW ranges between 22 to 30% (Nanda and Berruti, 2021). The organic and inorganic fractions differ depending on the location. A significant proportion of inorganic content can be found in coal-based regions. The percentage of MSW composition varies substantially in each Indian area. The fraction of combustibles grew as the amount of organic matter increased, boosting the practicality of the energy conversion process (Sebastian et al., 2019). Sources and impacts of municipal solid waste have been shown in Figure 1.

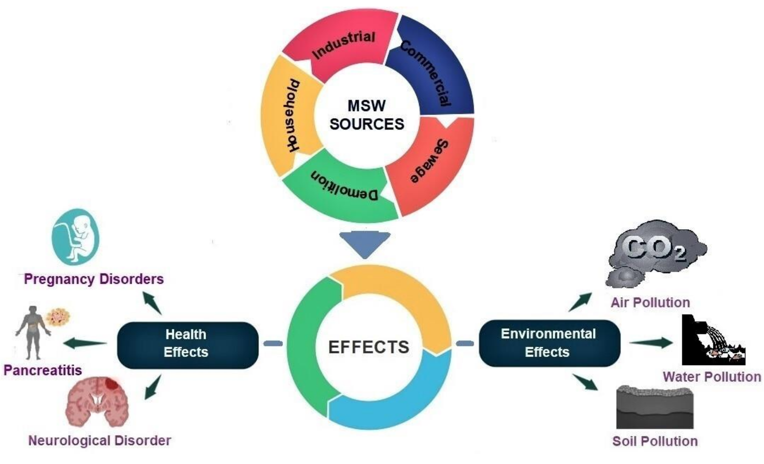

Figure 1. Sources and impacts of municipal solid waste

2.2 Health and Environmental Impacts

Improper management of MSW results in various types of contamination in the air, water, and soil. Careless disposal of MSW causes soil deposition and congestion in urban areas. Inadequate treatment of MSW contributes to the spread of pollution and disease. Climate change has been a major influence on national waste management. Municipal rubbish burning can have a significant impact on greenhouse gas emissions (Maiurova et al., 2022). Some recycling and recovery operations from municipal waste also result in the release of carbon dioxide and other gases. The organic fraction of municipal solid waste is a small amount of solid waste that has a negative influence on the environment and public health. The organic percentage of MSW, in particular, provides specific odors and features that attract insect vectors, rodents, and other infectious organisms (Ayilara et al., 2020). Many areas polluted with MSW serve as hubs for the spread of infectious and non-communicable diseases. Improper collection and disposal promote disease spread by increasing fly breeding opportunities. Dengue fever, malaria, and other rodent-borne diseases are among the vector-borne diseases linked to MSW pollution. The assessment of health risks has been an important method in identifying soil contaminated by municipal solid waste. In general, hazard index values less than one suggest non-carcinogenic effects, while values greater than one indicate the presence of carcinogenic substances in the sample. The carcinogenic factor was found to be greater than one, indicating a high health risk (Gujre et al., 2020; Adimalla et al., 2020). In terms of the environment, incorrect segregation and disposal of municipal solid waste impact animals due to their scavenging nature. The disposal of MSW contributes to the development of contagious and deadly illnesses by providing a breeding ground for harmful organisms. Burning MSW releases harmful gases. Furthermore, depositing solid waste in a specific location for an extended period releases gases such as methane, which harm living beings and environmental health. Clogging of water systems by MSW generates water pollution and terrible odors, making the area ideal for insect breeding (Abubakar et al., 2022). Therefore, effective treatment methods must be deployed to mitigate these negative impacts.

3. CURRENT STATUS OF MSW GENERATION OF INDIA

India, as a diverse country with vast disparities in geographical location and population, exhibits various waste-producing patterns. The rate of population growth in India is closely associated with Municipal Solid Waste (MSW) generation, as is overall capital augmentation. Based on specific projections, it is anticipated that 300 million tonnes of MSW will be generated and widespread by 2051. With waste generation, annual capital rises by around 1.33%. The urban Indian population generates 42 million tonnes of MSW per year (Soni et al., 2022). These MSW consist of 40-50% inert waste, 35-55% biodegradable matter, and just 5-10% recyclable content. According to a recent Central Pollution Control Board (CPCB) report, only 82% of the 1.18 lakh metric tonnes of MSW created is collected, with the remaining 18% littering the environment. A World Bank study indicates that, as of 2018, India has the highest garbage generation rate globally, with roughly 277.1 million tonnes generated annually. The growth of MSW generation concerning population is depicted in Figure 2 (Shahid et al., 2021).

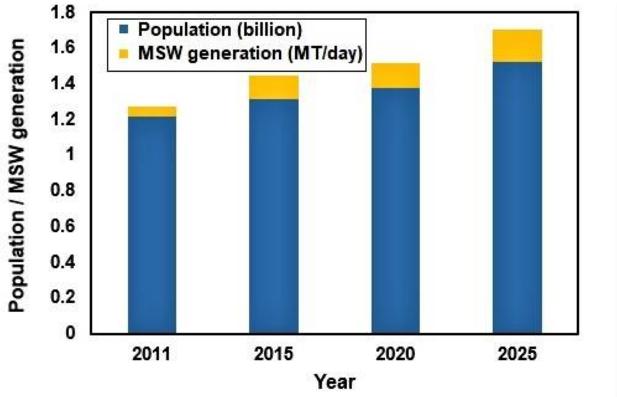

Figure 2. MSW generation with respect to population

By 2030, it is anticipated that 387 million tonnes will have been produced. Of the 82% of garbage collected, 20% is processed, while the remainder is discharged into the environment, leading to various types of pollution. The physical composition of MSW in different Indian cities has been tabulated in Table 1.

Table 1. Physical composition of MSW in different cities of India

City	Waste	Population range (million)	Physical composition							References
			Compostables (%)	Inert (%)	Glass (%)	Paper (%)	Textile (%)	Plastic (%)	Leather (%)	
Rajkot	594.8 t/day	2	5	10	0	3	3	9	65	Pujara et al., 2023
Mumbai	7025 tonnes/day	27.1	40	44	0.2	10	3.6	2	0.2	Sharma and Chandel, 2021
Dhanbad	440 tonnes/day	1.3	75	0.5	0.5	0.6	2.4	7.7	2.4	Mboowa et al., 2017
Kharagpur	95 metric tonnes/day	0.29	41.3	18.8	0.3	10.9	10.6	9.9	0.6	Sajid et al., 2022
Delhi	11.3 k tonnes	32	72.6	0.8	0.6	0.6	4.5	4.2	2	Ramaiah et al., 2017

City	Waste	Population range (million)	Physical composition							References
			Compostables (%)	Inert (%)	Glass (%)	Paper (%)	Textile (%)	Plastic (%)	Leather (%)	
Kolkata	3000 tonnes/day	8	50.56	29.6	0.34	6.07	3.86	4.88	3.86	Chattopadhyay et al., 2009
Puducherry	215 t/d	0.3	65	21.2	12.5	30	32.4	10.4	14.6	Pattnaik et al., 2010
Varanasi	800 mt/d	1.6	31.9	2.8	6.7	9.6	10.6	22	5.7	Srivastava et al., 2014
Chennai	3000 t/d	6.4	64-78	25-30	0.2	12	1.9	3.6	0.2	Joseph et al., 2012
Bangalore	3600 t/d	13.6	60	-	4	12	14	14	1	Ramachandra et al., 2018
Lucknow	1500 t/d	4.5	45.99	12	17.7	4.6	19.06	2.6	3	Rawat et al., 2022
Hyderabad	3000 t/d	6.9	50-60	20	1	8.13	4	9.22	3	Korai et al., 2016.

The major producers of municipal solid waste in India are the megacities of Delhi, Mumbai, Chennai, and Kolkata due to their dense populations and economic activity. Since garbage output is directly related to city per capita income, the volume of waste generated differs among cities. In Chennai, the daily waste generation rate is approximately 0.62 kg/c/day. Every day, 1000 tonnes of demolition waste and 400 tonnes of rubbish waste are generated (Esfilar et al., 2021). Overall, Chennai produces approximately 9000 tons per day, of which only 10-20% is processed. Figure 3 illustrates the solid waste generated per day in India versus the percentage treated and landfilled over the years 2015-2021 (CPCB Report – 2021).

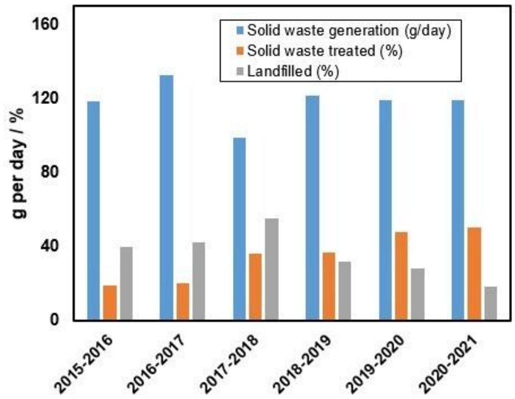

Figure 3. Solid waste generated per day in India vs treated and landfilled % over years 2015-2021 (CPCB Report – 2021)

All of this waste must be properly gathered and treated to improve environmental preservation and drive national capital growth.

4. PRETREATMENT TECHNIQUES

Municipal Solid Waste contains complex compounds that may impact the treatment and disposal processes. Pretreatment procedures facilitate the removal of complicated molecules from MSW. The composition of MSW is depicted in Figure 4.

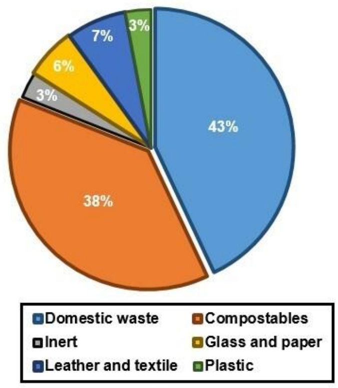

Figure 4. Composition of Municipal Solid Waste

The organic part of MSW, for example, contains lignin and hemicellulose molecules that can be removed using proper pretreatment procedures. Certain pretreatment procedures also help reduce crystallinity, which boosts the final fuel yield produced from MSW (Joseph et al., 2020). Thus, the key goals of MSW pretreatment are to reduce trash dumping, boost product yield, and simplify conversion operations. Figure 5 depicts the different pretreatment methods employed for municipal waste-based energy generation.

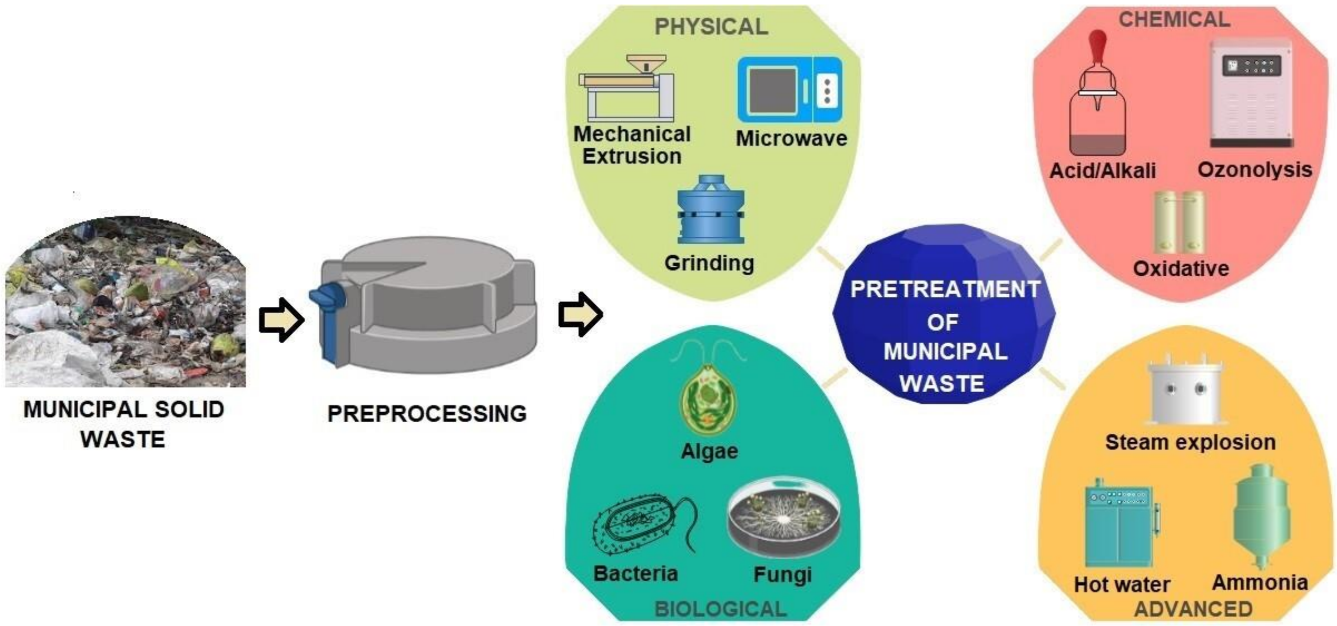

Figure 5. Different pretreatment methods employed for municipal waste based energy generation

4.1 Physical

Physical methods, such as crushing or breaking down MSW to increase the waste substrate's surface area, are one type of processing. Milling, often known as grinding, is a physical pretreatment procedure used to reduce the size of MSW particles. A ball mill is widely used to change the crystalline form of substances and reduce their size. It also enhances particle digestibility (Panigrahi et al., 2019). Xie et al. (2023) used ball milling technology to pretreat municipal solid waste. This technology has been used in conjunction with the flotation procedure to improve pollutant removal. The ball milling process aided in dioxin breakdown by removing carbon and fly ash. Significant mitigation in dioxin content has been observed after the ball milling pretreatment process (Xie et al., 2023). Anaerobic digestion of MSW has shown that physical pretreatment using revolving drums is a useful technique for improving the organic fraction's digesting capacity. This organic fraction is then employed in the anaerobic digestion process. Gikas et al. (2018) evaluated a rotary drum-based process for pretreatment of municipal solid waste for anaerobic digestion-based biogas production. The rotary drum pretreatment method is successful in removing biodegradable materials from MSW. Because of the separation of the biodegradable fraction, moisture content was substantially reduced, and biogas yield improved following the pretreatment procedure (Gikas et al., 2018). Ultrasonication is one of the green approaches used in MSW treatment. The resistant organic part of MSW was treated to cavitation-based ultrasonic radiation. The creation of cavitation bubbles is caused by ultrasonic waves moving through MSW material. In the reaction environment, these bubbles generate shear forces and pressure differences. Thus, during the ultrasonic pretreatment procedure, the complex network of MSW will be degraded. Rasapoor et al. (2018) tested ultrasonic-pretreated MSW in a pilot-scale digester for energy production. A 6% solid content MSW mixture was treated for half an hour at a power density of 0.2 W/mL. The sonication treatment resulted in the highest cumulative biogas yield (Rasapoor et al., 2018). A few positive outcomes of a physical-based pretreatment method for municipal solid wastes are the elimination of foul odors, lower energy consumption, and a simpler implementation process. Thus, physical methods of pretreatment are the primary treatment processes that can be easily adopted for MSW management without much energy requirement. Physical pretreatment techniques show a great deal of promise for improving the management of municipal solid waste (MSW) by streamlining the processes of size reduction, separation, and sorting. This will ultimately lead to the recovery of resources and a decrease in the environmental impact of disposing of garbage.

4.2 Chemical

The chemical approach to pretreatment is the traditional procedure for MSW, involving the use of acids or alkalis to degrade organic molecules into convertible fractions. Common alkali treatment methods include pretreatment with acid, alkali, oxidant, and hot water. The production of bioethanol from MSW often involves acid and alkali treatments. Waste particles enlarge as a result of solvation and saponification during alkali treatment, increasing the surface area of the MSW and facilitating microorganism access to the conversion process (Das et al., 2021). Dasgupta and Chandel (2020) employed alkali pretreatment to produce biogas from the organic part of MSW, using NaOH treatment for 24 hours. They discovered a 19-34% increase in cumulative biogas after NaOH pretreatment. Acid treatment degrades lignin content and induces hydrolytic bacteria adaptation to the new environment. Acidic treatment commonly causes lignin condensation and precipitation, as well as hemicellulose hydrolysis to mono-sugars. However, the use of powerful acids can result in the creation of inhibitory compounds such as furfural, so the use of dilute acids is typically favored for MSW treatment (Dasgupta and Chandel, 2020). Ebrahimian and Karimi (2019) utilized organosolv pretreatment to produce MSW-based biofuel, mixing acetic acid and butyric acid in a reaction solution at 60°C for 30 minutes. A 1% acetic acid addition eliminated 75 g of xylan and 117 g of lignin. The hydrolysates of acid-pretreated MSW samples contained considerably less starch. The pretreatment technique enhanced the overall output of ethanol and hydrogen (Ebrahimian and Karimi, 2019). Thus, the qualities and types of MSW substrate have a wide range of influence on the chemical pretreatment process. Furthermore, chemical treatment procedures are ineffective for biodegradable MSW components. Chemical pretreatment techniques for managing municipal solid waste (MSW) offer benefits such as improved biodegradability and effective organic matter breakdown. However, they also have drawbacks, including the possibility of chemical contamination and expensive operating expenses. Methods of MSW pretreatment – conditions, significance, and application – are detailed in Table 2.

Table 2. Methods of MSW pretreatment – conditions, significance and application

Pretreatment type	Pretreatment method	MSW substrate	Conditions	Inferences	Application	References
Physical	Ultrasonication	Complex MSW – Fruit, paper, food and PVC	Frequencies – 80 kHz Time – 2h Power – 400 W	❖ Increased activation energy of samples ❖ Rough surface area	Reduced pyrolysis operating temperature	Fang et al., 2019
Physico-chemical	Hydrothermal	MSW – Cooked food waste, garden waste, Vegetable and food waste	Temperature – 140 °C Time – 30 min Heating rate – 10 °C/min	❖ Improved Solubilization of organic matter ❖ High cellulose reduction	Methane generation – 68.6%	Dasgupta and Chandel, 2019
Chemical	Alkaline	Municipal waste activated sludge	NaOH - 30% Temp – 35 °C Time – 60 min	❖ Disintegration of sludge flocs ❖ Minimize the requirements of additional reagents	Methane production – 267.1 mL/g VS	Budych-Gorzna et al., 2021
Physico-chemical	Hydrothermal	Organic fraction of MSW	Temp – 130 °C Time – 60 min	❖ Increased glucose concentration ❖ Removal of lignin and hemicellulose	Ethanol yield – 70.86%	Mahmoodi et al., 2018
Physical	Washing	MSW incineration ash	Vibrating time – 30 r/min Time – 40 min	❖ Decreased metal concentration	Additive for strengthening cement – stabilized soil	Liang et al., 2020
Chemical	Organosolv	MSW – Starch, Kitchen, garden, and paper waste	Ethanol – 85 % Time – 30 min Temp – 120 °C	❖ Increased delignification and hemicellulose hydrolysis	Butane, acetone, and ethanol (ABE)	Farmanbordar et al., 2018
Biological	Enzymatic	Organic fraction of MSW	Temp – 50 °C pH – 4.5	❖ Maximize organic matter solubilization	Methane – 189.2 mL/g VS	Mlaik et al., 2019
Physical	Thermal	MSW ash	Temp – 105 °C Time – 24 h	❖ Increased alkalinity ❖ Mitigate hydration and expansion	Resource utilization in mortar	Joseph et al., 2020
Physico-chemical	Organosolv	Organic fraction of MSW	Ethanol – 85 % Time – 30 min Heating rate – 4 °C/min	❖ Increased delignification and hemicellulose hydrolysis ❖ Decreased starch content	Hydrogen – 151 L/kg	Ebrahimian and Karimi, 2019
Physico-chemical	Bio-Ionic liquid	Non-recyclable MSW	Temp – 140 °C Time – 3 h	❖ Improved fermentation performance ❖ Minimal downstream separation	Methyl Ketones – 1145 mg/L	Yan et al., 2019
Chemical	Acid	Organic fraction of MSW	Formic acid – 5% Temp – 80 °C Time – 70 min	❖ Promotes biological conversion ❖ Improved compound degradation	Hydrogen yield – 31.6 mL/g	Cesaro et al., 2020

4.3 Biological

The biological pretreatment approach utilizes microorganisms and their cultivation to increase the solubility of MSW components. The organic fraction of MSW, comprising covalent and non-covalent bonds, can be broken down during the biological pretreatment process. The most popular biological pretreatment techniques include the utilization of aerobic and anaerobic organisms. MSW is primarily subjected to anaerobic digestion for biogas and biomethane production. This technique promotes rapid microbial development, thereby increasing the hydrolysis rate of MSW's organic fraction. Exposure of MSW to aerobic organisms before composting and other biological conversion processes improves biofuel production. However, the main goal of the biological approach is to increase the number of microbial species in MSW management, followed by the production of the enzymes needed for MSW hydrolysis in the digestion stage (Zamri et al., 2021; Tshemese et al., 2023). Dehkordi et al. (2020) conducted a case study on biogas production from MSW using a biological treatment approach. Composting pretreatment results in a greater microbial specific growth rate. Furthermore, physical separation of methanogens from acidogens results in increased biomethane synthesis (Dehkordi et al., 2020). Hemicellulose, glucanases, glucoamylase, and xylanases are the most common enzymes in the hydrolysis improvement process during enzymatic pretreatment. In some circumstances, fungal treatment of the substrate provides sufficient organic acids and nutrients for the proliferation of anaerobic organisms. In anaerobic-based MSW conversion systems, biological pretreatment reduces retention time while increasing digestate quantity. In summary, biological pretreatment techniques offer advantages including natural decomposition, lower energy usage, and the potential for resource recovery through composting or biogas generation, making them a viable option for managing municipal solid waste (MSW). Widespread adoption might be hampered by issues such as lengthier processing times, sensitivity to environmental factors, and the requirement for specialized knowledge. Despite these disadvantages, the sustainability of biological pretreatment emphasizes the significance of shifting towards more eco-friendly waste management techniques.

5. SUSTAINABLE TREATMENT TECHNOLOGIES

Municipal solid waste comprises a substantial amount of organic complex that can be collected for use in the production of bioenergy and biofuel. The recovery of useful energy from MSW has been proposed as a waste management and energy disposal alternative. There are two ways to recover energy from the organic part of MSW.

5.1 Thermal Conversion

The thermal conversion process promotes the degradation of organic matter to bio-fuel. In thermochemical conversion processes, reactions are often carried out at high temperatures in an anoxygenic or oxygenic atmosphere. These thermal-based conversion technologies can recover high-value fuels and bioenergy (Zhang et al., 2020). Thermal conversion of organic fraction of municipal solid waste was illustrated in Figure 6.

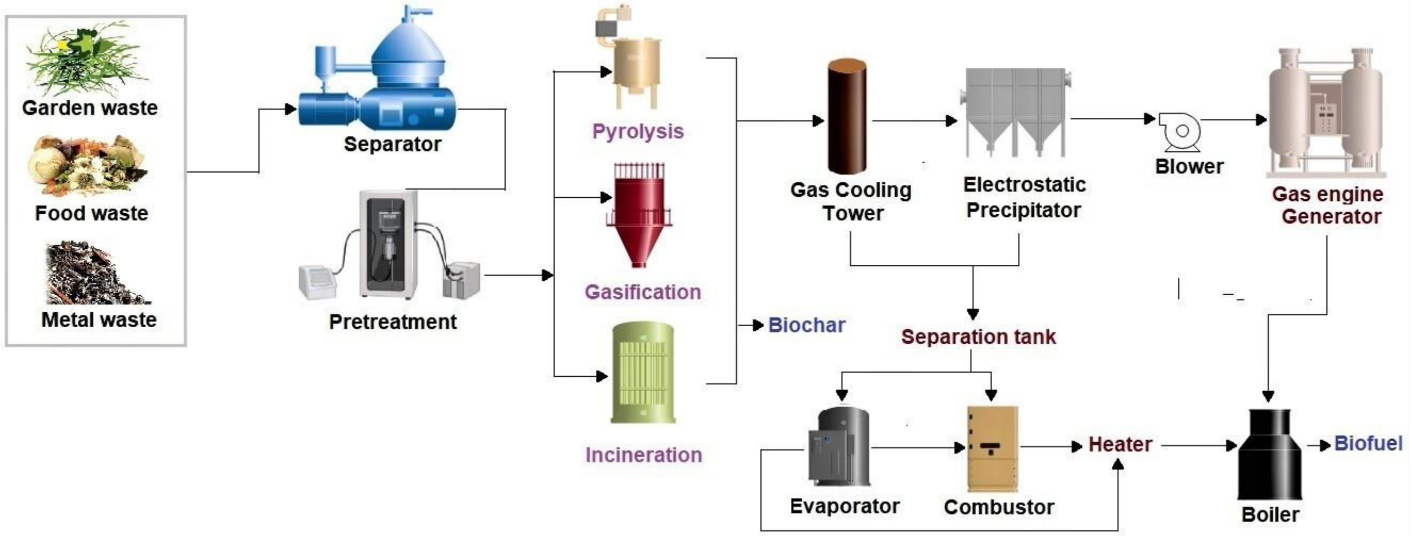

Figure 6. Thermal conversion of organic fraction of municipal solid waste

5.1.1 Pyrolysis

Pyrolysis is a thermochemical process that involves the irreversible conversion of various organic and inorganic sources into value-added biofuels. In the current environment, pyrolysis aids in the conversion of municipal solid waste into liquid biofuels such as bio-oil. Pyrolysis results in both chemical and physical compositional changes. It is categorized into three types based on the reaction conditions: slow, flash, and quick. Slow pyrolysis is carried out as a batch process on a small scale at temperatures below 300 °C with heating rates ranging from 0.1 to 0.8 °C/s (Hasan et al., 2021). The slow pyrolysis process requires a longer residence time since it occurs at low temperatures. The fast pyrolysis process occurs at temperatures ranging from 400 to 700 °C. The heating rate is around 10 to 100 °C/s, and the residence time is approximately 0.5 to 2 s (Hasan et al., 2021). The last type, flash pyrolysis process, requires higher temperature ranges - 700 to 900 °C - and a very high heating rate of 1000 °C/s. Because the reaction occurs at high temperatures, the flash pyrolysis process requires a very short residence time. Yang et al. (2018a) performed slow pyrolysis of MSW to recover energy from the waste feedstock. For the liquid product production, the pyrolysis process was carried out at 450 °C. At 850 °C, the hydrogen output increased dramatically from 2 to 40%. The pyrolysis approach was employed in the research process with a residence time of 7-17 s (Yang et al., 2018a).

Microwave-assisted pyrolysis is a cutting-edge approach for treating municipal solid waste. It has various advantages over conventional pyrolysis, including improved heat transmission, a simpler mechanism, and a shorter processing time. Suriapparao et al. (2022) employed microwave-assisted pyrolysis to treat MSW while also recovering polycyclic aromatic hydrocarbons (PAH) from the garbage. For the MSW conversion, microwave power ranging from 300 to 600 W was used. The researchers detected approximately 60% gas with char and bio-oil production. At 600 W power, the highest PAH recovery of 84.5% was achieved (Suriapparao et al., 2022). In conclusion, the treatment of MSW by pyrolysis has great potential since it provides benefits including effective waste conversion into useful products like syngas and biochar, less reliance on landfills, and a reduced environmental impact. However, it is imperative to tackle obstacles including elevated initial investment expenses, the requirement for careful emission monitoring, and probable uncertainty concerning the technology's scalability.

5.1.2 Gasification

Gasification is a technique operating within a mid-temperature range between combustion and pyrolysis temperatures. Temperatures exceeding 650 °C have been utilized in the gasification process, in the presence of air, steam, or oxygen. Typically, the conversion of feedstock into bioenergy occurs in low oxygen atmospheric circumstances. At different temperatures, both exothermic and endothermic reactions occur simultaneously during the gasification process. Processes such as the water-gas shift reaction, steam reforming, methanation, hydrogasification, and the Boudouard reaction are all integral to the gasification process (Saebea et al., 2020). In the gas shift reaction, carbon is converted into hydrogen and carbon monoxide. Methane gas is created during hydrogasification, and the Boudouard reaction aids in the production of CO_2. Gasification can be used to reduce heterogeneous processes to homogeneous reactions. The total process consists of four steps: drying, pyrolysis, oxidation, and gasification. At temperatures ranging from 100 to 130 °C, the drying phase evaporates the moisture content of the MSW feedstock. The pyrolysis zone continues with reaction temperatures between 500 and 550 °C under limited oxygen conditions, resulting in the generation of liquid products with biochar vaporization (Wang et al., 2023; Faraji and Saidi, 2022). Biochar with improved surface characteristics is formed in large quantities in the combustion or oxidation zone at temperatures ranging from 800 to 1000 °C. The pyrolyzed biochar is converted into a gas mixture in the final gasification zone. Slag, which is formed from garbage such as MSW, is the end product of the gasification process. For waste-based conversion, a two-stage gasification process consisting of a gasifier chamber and a syngas chamber is commonly used (Chanthakett et al., 2021). Jung et al. (2019) defined municipal solid waste fuel industrial gasification. Biochar was produced as a byproduct of the industrial gasification of MSW. The syngas was produced through the waste regeneration process (Jung et al., 2019). Chen et al. (2020) produced hydrogen-enriched syngas from portions of municipal solid waste in a similar manner. For gasification, a tube reactor with a process temperature of 757.65 °C and a residence duration of 22.26 minutes was used. Under these conditions, the optimum H2 production was 41.36%. Using air as a gasifying agent enhanced overall gas output (Chen et al., 2020). Researchers have also conducted a few techno-economic analyses on the gasification-based conversion of MSW. According to a recent study, the production of hydrogen from MSW is more favorable in terms of energy efficiency and environmental friendliness (Sun et al., 2021). As a result, gasification has been regarded as a common technology and a valuable mechanism in MSW treatment and management. A viable option for treating MSW is gasification, which efficiently converts trash into syngas for energy generation, requires less landfill space, and may recover resources. Nonetheless, there are obstacles that must be overcome, including large capital costs, intricate operations, and the requirement for careful byproduct and emission management. Despite these disadvantages, gasification has the potential to significantly advance environmentally friendly waste management techniques and support efforts to conserve the environment and produce energy. Table 3 shows the thermal conversion methods and their conditions for the treatment of MSW.

Table 3. Thermal conversion methods and its conditions for the treatment of MSW

Feedstock	Pretreatment	Thermal conversion type	Sub-type	Conditions	Research observations	Product	References
Municipal solid waste + Paper mill sludge	Ultrasonic	Pyrolysis	Batch	Temp – 110-900 °C Heating rate – 30 °C/min	Increased activation energy Rapid pyrolysis	Biochar	Fang et al., 2019
Unsegregated MSW	-	Pyrolysis	Single stage	Temp – 550 °C Heating rate – 30 °C/min	Significant influence of plastic components	Bio-oil	Chhabra et al., 2020
Mixed MSW	Physical	Gasification	Downdraft fixed bed	Feed rate – 4.4 g/min Temp – 300 °C	Improved ~90% removal efficiency of sulphur Increased total syngas yield	Syngas	Chan et al., 2019
Organic fraction of MSW	Mechanical	Pyrolysis	Non-catalytic	Temp – 500 °C Heating rate – 15 °C/min	Degradation of polycyclic aromatic compounds	Biogas	Wang et al., 2020
MSW+wheat straw	Physical	Gasification	Continuous fluidized bed	Temp – 600-900 °C	Increased hydrogen concentration in syngas	Syngas	Zhao et al., 2021
MSW	Physical	Gasification	Fixed bed drown draft	Temp – 835-849 °C Steam flow rate – 104 L/h	Potential adsorbents in water treatment	Biochar	Jung et al., 2019

Feedstock	Pretreatment	Thermal conversion type	Sub-type	Conditions	Research observations	Product	References
Organic fraction of MSW and digestate	Thermal	Pyrolysis	Bench scale	Temp – 450 – 650 °C Rate – 15 °C/min	High acid abundance Low water yield and high organic fraction	Gas	Wen et al., 2021
Organic fraction of MSW	Mechanical	Pyrolysis	Slow	Temp – 450-850 °C	Relatively small effect of moisture content	Bio-oil	Yang et al., 2018a
Organic fraction of MSW	-	Pyrolysis	Intermediate	Temp - 500 °C	Heavy organic generation from condensation and pyrolysis	Bio-oil	Yang et al., 2018b
Municipal sludge	-	Plasma gasification	Plasma gasifier	Temp – 2500 °C	Simulation – less environmental impact process	Hydrogen	Qi et al., 2021
MSW	Physical	Gasification	Multistage downdraft	Temp – 500-600°C	Multistage inlet - improved performance	Syngas	Saleh et al., 2020

5.1.3 Incineration

Incineration is a thermal-based conversion process that can utilize both processed and raw waste material to reduce waste and produce energy. The burning process must be carried out at temperatures ranging from 800 to 1000 °C. It entails the conversion of MSW into heat and other biofuels via combustion. Bottom ash, which comprises carbon residue, is the solid residue of non-combustible materials. The key elements of energy recovery-based incineration are waste processing, burning, energy recovery, and emission clean-up (Zhu et al., 2021; Makarichi et al., 2018). MSW is collected and blended in order to achieve optimal blending and energy output. The energy content of raw MSW can be increased by drying and removing recyclable components. The numerous types of incinerators used for MSW incineration are fluidized bed, rotary kiln, and moving grate. In terms of MSW treatment, fluidized bed incinerators have lately gained popularity due to their increased efficiency. To reduce particle size and achieve homogeneity, some pretreatment techniques are required (Fan et al., 2022; Lasek et al., 2021). The additional air supply in the rotary kiln incinerator ensures that the waste is completely burnt. The moving grate incinerator, which has a descending grate that gradually travels down into the combustion chamber, is frequently used for MSW treatment. In Indian cities, the incineration procedure for biological garbage is largely limited. The majority of MSW incineration investigations have been carried out with residues generated throughout the process (Malav et al., 2020). Blasenbauer et al. (2023) examined the bottom ashes produced by the MSW incineration processes via grate and fluidized bed incinerator. The study concluded that bottom ash from fluidized bed incinerators produced higher-quality recyclables. However, a large amount of fly ash is produced throughout the process, which must be disposed of (Blasenbauer et al., 2023). Although 80-90% of MSW volume is reduced, hazardous compounds such as airborne dioxins and incombustible ash with higher inorganic content are produced. Incineration remains a significant part of MSW management, providing advantages like resource recovery, reduced reliance on landfills, and energy recovery. However, future works should focus on improving the control of emissions and mitigating harmful impacts on the ecosystem. Despite challenges, strategic planning will develop incineration as a suitable MSW management technique.

5.2 Biological Conversion

5.2.1 Fermentation

Approximately 30-40% of MSW consists of lignocellulose compounds, with cellulose-based components accounting for 50% of the total. The presence of food and paper in MSW contributes to its biodegradability. MSW can be converted into biofuels such as biobutanol and bioethanol in three steps: pretreatment, hydrolysis, and fermentation (Ebrahimian et al., 2023). In general, three stages of MSW fermentation occur: separate hydrolysis and fermentation, simultaneous saccharification and fermentation (SSF), and combined hydrolysis and fermentation. Hydrolysis and fermentation are carried out concurrently in the SSF-based conversion process. Glucose fermentation by microbial organisms is completed in a single step at an ideal temperature range of 37-40 °C. This SSF technique eliminates the need for microbial culture in the hydrolysis and conversion processes. Other advantages of the SSF approach include improved enzyme stability and shorter duration (Hemansi and Saini, 2023; Boonchuay et al., 2021). Enzymatic hydrolysis and biomass saccharification are combined in the SHF process at an optimal temperature. Compared to the SSF procedure, the SHF approach uses fewer enzymes. However, the SHF process has a much greater capital cost due to the separate execution of each step. Acidogenic fermentation is a common method for converting the organic part of MSW, as it serves as a suitable substrate for acid generation. The process occurs in two stages, the first of which includes the breakdown of complex organics into simpler monomers. Acid production occurs as a result of organic reduction in acidogenesis and acetogenesis. Additionally, photo-fermentation is used (Soomro et al., 2020). Allegue et al. (2020) employed a unique technique for MSW conversion by combining thermal treatment with bio-based approaches such as photo-fermentation and anaerobic digestion. In this regard, heat treatment improves the degradability of MSW. The diluted liquid fraction of MSW was utilized as the organic substrate in the batch photo-fermentation studies. About 80% of the MSW's organic content is consumed by mixed phototrophic bacteria, producing about 57% efficiency (Allegue et al., 2020). Despite many benefits, challenges like long process time, the need for consistent MSW feedstock quality, maintenance of microbial culture, and toxicity aspects limit its commercial-scale application.

5.2.2 Anaerobic digestion

A complex digestion process that converts organic materials into fertilizer and fuel through a sequence of metabolic processes is anaerobic digestion. Under anaerobic conditions, the process is carried out with the assistance of anaerobic bacteria. The deployment of this technique can dramatically lower the BOD and COD levels in municipal waste streams (Biase et al., 2019; Feng et al., 2019). The anaerobic digestion process consists of four steps. Complex organics are initially broken down into simpler ones. Hydrolysis reactions occur in the first - rate-limiting stage, resulting in fatty acid production along with other volatile and hazardous byproducts. Prior to the process, MSW pretreatment accelerates the hydrolysis reaction. The reduction of VFA (volatile fatty acids) in the acidogenesis stage produces short fatty acids with hydrogen generation (Yadav et al., 2022; Zhang et al., 2023). Acetic acid production from organic acids occurs in the third stage, acetogenesis. Methane is created from acetic acid in the last phase using methanogens. Steps involved in anaerobic digestion-based treatment of municipal solid waste have been pictorially represented in Figure 7.

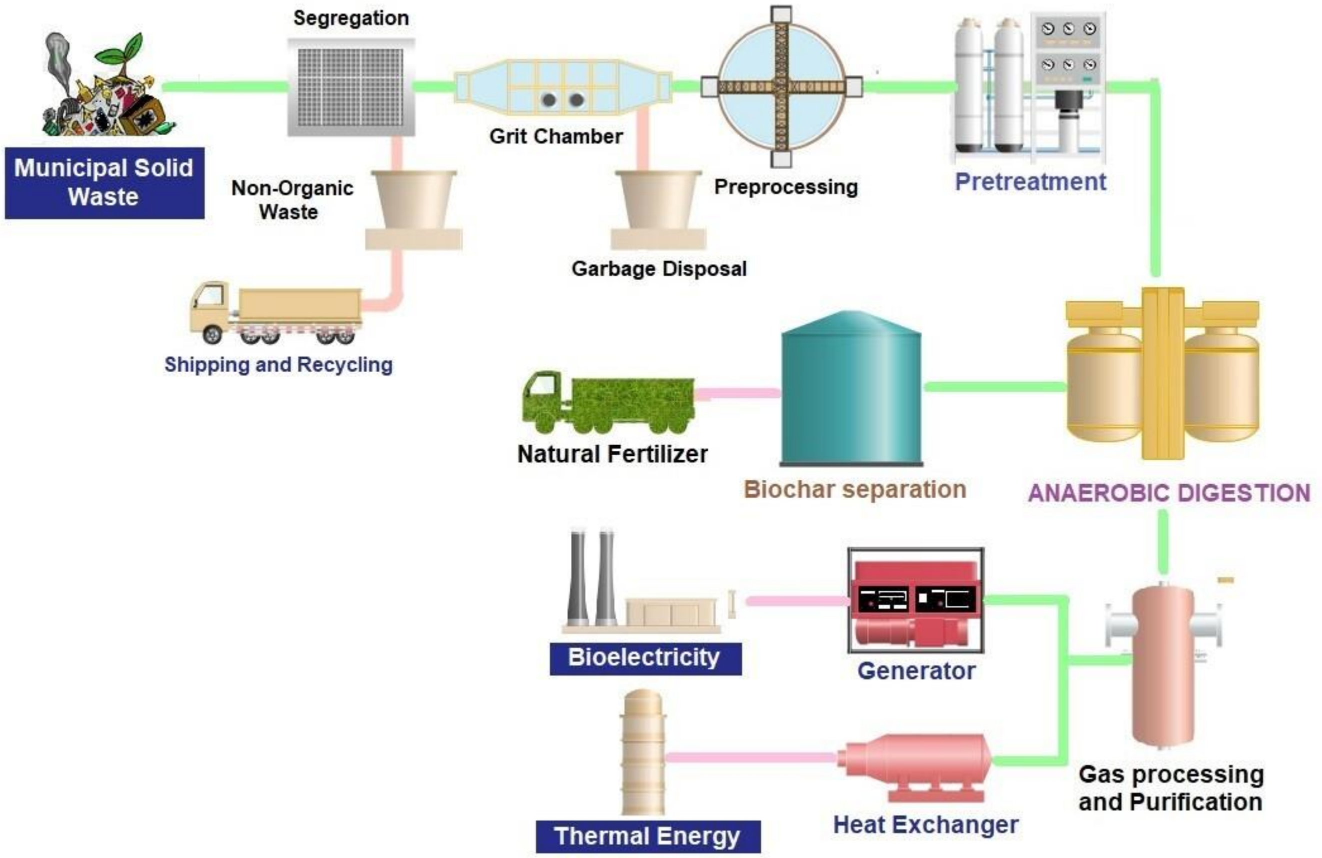

Figure 7. Steps involved in anaerobic digestion based treatment of municipal solid waste

There are various types of anaerobic digestion methods based on criteria. It is classified as batch or continuous anaerobic digestion based on its operating design. In reactor design, plug flow and fully mixed reactors were more common in the recent past. This process is carried out by hydrolytic, methanogenic, fermentative, and acetogenic organisms, mostly bacteria (Zhong et al., 2022; Kumar and Samadder, 2020). Several factors influence the gas generation process from MSW via anaerobic digestion. Loading rate, C/N ratio, pH, temperature, and retention period are all important factors. Shamurad et al. (2020) investigated how anaerobic digestion of MSW improved methane productivity. The acidogenic reactor requires 10 days of hydraulic retention time for accelerated hydrogen generation. In the two-stage anaerobic digestion, the archaeal community observed a distinct preponderance of hydrogenotrophic organisms with increased stability and high methane generation (Shamurad et al., 2020). The primary operational elements influencing anaerobic digestion efficacy are organic loading rate, pH, carbon ratio, total solid content, redox potential, temperature, and mixing. Feng et al. (2019) examined the microbial community in MSW leachate anaerobic digestion for methane production. The sequencing examination of the AD microbial community revealed a predominance of acetotrophic and hydrogenotrophic species. The maximal productivity of 117.5 mL CH_4/g VS d resulted in a 2.34-fold increase in methane generation (Feng et al., 2019). The sensitivity of the AD process to toxicants limits its process efficiency. As a result, certain changes must be made to improve process efficiency. Anaerobic digestion is emerging as an innovative approach for treating MSW, using organic waste to produce digestate rich in nutrients for improved soil and biogas for clean, renewable electricity. Future approaches should prioritize technical refinements to boost efficiency and scalability, together with policies supporting waste diversion and circular economy activities, despite constraints such as early infrastructure costs and sensitivity to feedstock composition. Table 4 gives details regarding previous studies on anaerobic digestion of MSW for biogas and biomethane production – inoculum, reaction parameters, and yield.

Table 4. Anaerobic digestion of MSW for biogas and biomethane production – inoculum, reaction parameters, and yield

Microbial Inoculum	Type of digester	HRT	Temp (°C)	Solid loading	Yield	Findings	References
Mesophilic anaerobic digester sludge	Batch	2.5 h/d	37	0.1348 kg/h/d	Methane recovery – 70%	❖ Higher organic processing capability ❖ Lower solid washout	Dastyar et al., 2021
Thermophilic sludge inoculum	Two stage batch	72 h	55	-	Biochemical methane potential – 250 mL/g	❖ High reactor performance ❖ Easier accessibility of MSW substrate	Amodeo et al., 2021
Thermophilic granular sludge	Single stage batch	24 h	55	6 VSS/L	Methane – 117.3 mL/g. d	❖ COD degradation efficiency – 81.8% ❖ Effective utilization of organic matter	Feng et al., 2019
Biogas plant inoculum	Batch	30 d	35	-	Methane – 37%	❖ Process efficiency – 60% ❖ Reduction in COD	Lucian et al., 2020
Anaerobic liquid digestate	Bottle digester	122 d	40	4.22 kg/m^3.d	Methane – 0.176 m^3/kg VS	❖ Reduced particle size ❖ Improved stability in methane generation	Basinas et al., 2021
Anaerobic sludge and cow dung slurry	Single and two stage Batch	12 d	40	-	Biohythane production with 25% methane	❖ 46% reduction in COD ❖ Restrained pH – Lower production	Prashanth Kumar et al., 2019
Biogas inoculum	Two stage reactor	10-20	37	<2 g/L.d	Methane – 227 mL/g	❖ Higher water saturation ❖ High hydrolytic activity	Nasir et al., 2020
Residual anaerobic digestate	Semi-continuous	20 d	35	1 g Vs/L/d	Methane potential – 422 NmL/g VS	❖ Slow decrease in TS concentration ❖ Efficient biodegradable matter	Fazzino et al., 2021
Digested sewage sludge	Batch	42 d	35	2-3 kg/m^3.d	Methane – 98%	❖ Short retention time ❖ Reduced VFA accumulation	Sailer et al., 2020
Mesophilic anaerobic digestate	Continuous	20 d		2.5 – 5 g/L.d	Methane – 527 mL/g VS	❖ Higher volumetric methane productivity ❖ Dominance of hydrogenotrophic methanogens	Shamurad et al., 2020
Plant	Batch	21 d	53	0.07 VS	Methane yield – 330-366 NL/kg	❖ Decreased toxicity ❖ Increased efficiency in VS reduction	Bona et al., 2020
Methane fermenter digestate	Pilot scale two stage	400 d	32	2.5 kg/m^3.d	Biogas – 52 N m^3/ton	❖ High organic removal performance ❖ Efficant nutrient recovery	Nguyen et al., 2020
Anaerobic mesophilic sludge digestate	Batch	20 d	37	2.79 kg/m^3.d	Energy potential – 28 MWh/d	❖ Suppression of influent COD mineralization ❖ Higher energy balance	Guven et al., 2019

6. MSW MANAGEMENT POLICIES IN INDIA

The Pollution Control Board of India has taken several steps to reduce and track MSW management. The SWACHH Bharat mission and MSW rules are part of the legal policy framework for MSW management. Solid waste management has been designated as a state topic in Schedule 12 of the 74th Amendment to the Indian Constitution. Despite widespread support for MSW collection, segregation, and treatment, difficulties with processing and proper disposal must be addressed urgently. Municipal Solid Waste (Management & Handling) Rules were first introduced in India by municipal authorities in the year 2000 (Kulkarni, 2020; Priti and Mandal, 2019). These rules are normally applied to all local authorities in order to collect, segregate, store, transport, and dispose of waste after processing treatment. The major goal of MSW rules - 2000 is to locate suitable land for MSW disposal and treatment. This rule emphasizes door-to-door MSW collection, segregation, transportation, the establishment of processing facilities, and the development of sanitary landfills. Each local authority is responsible for the application of these guidelines as well as the development of the MSW management system's infrastructure. The secretary in charge of the Pollution Control Board is ultimately responsible for monitoring compliance with MSW processing criteria (Khan et al., 2022; Prajapati et al., 2021; Xiao et al., 2020). Municipal authorities should also obtain proper authorization from the pollution control board. Because the majority of MSW disposal sites are open dumps, technical support and high-cost engagement are required to optimize landfill site operations. Some composting and anaerobic digesting facilities might be economically implemented if a substantial investment in treatment plants is envisaged. However, a number of restrictions - unorganized trash disposal, a lack of adequate disposal sites, a lack of financial management, and waste processing capability - hamper its deployment. In the year 2015, the draft was recirculated and amended as Solid Waste Management Rules - 2015 (Thakur et al., 2021). The revised waste management guidelines address technical, financial, planning, and legal elements of MSW management. The rules cover levying a service fee for the management process, preparing mandatory plans, selecting appropriate landfill sites and disposal, environmental clearance, monitoring emission standards, and reporting MSW management data to the appropriate government authorities on an annual basis. However, numerous gaps in the rules limit the law's broad spectrum of waste mitigation. Processing of sanitary waste has been lacking in the treatment process due to the variety of unique categories for different MSW (Wang and Yu, 2021).

Transportation for secondary storage vehicles has been a problem, resulting in social consequences. Domestic waste processing, on the other hand, has been entrusted to the jurisdiction of state pollution control bodies, which makes monitoring difficult. Thus, in recent years, a seven-step approach to MSW planning has been applied. Initially, legal policies and framework for MSW management are identified, followed by gap analysis and assessment of the current situation, stakeholder consultation for planning, draft plan preparation, implementation schedule, plan validation, and council approval (Mani and Singh, 2016; Bello et al., 2022; Ganguly and Chakraborty 2021t). The initial SWM regulations - 2016 served as a significant step forward; however, they failed to address the improvements and issues regarding sanitation and waste management in various sections of the country.

7. FUTURE OUTLOOKS

Waste segregation, depending on its source, has long been a time-consuming process in Indian municipalities. To facilitate proper Municipal Solid Waste (MSW) processing, it is essential to establish adequate segregation facilities. Substantial funding is necessary for effective assessment and development planning. Significant steps need to be taken to address the infrastructure's most challenging aspects concerning treatment, processing, and recycling. MSW contains valuable components that can be extracted and repurposed for various uses.

To characterize the MSW components generated annually, a new survey must be conducted. However, acquiring the desired statistical results requires collecting a considerable amount of data. Certain types of energy are necessary for MSW pretreatment to reduce reactor capacity and promote reactant flow, thus mitigating environmental impact. The performance of pretreatment technology concerning environmental concerns must be successfully implemented.

Physical concerns, such as heavy metals and other harmful substances, can arise during MSW composting. Utilizing MSW composts in agriculture can enhance structural stability and soil quality. The heterogeneity of the organic part of municipal waste has been a significant obstacle to waste-to-energy conversion. An effective digester for managing high solid content MSW has yet to be developed. Prioritizing the energy demand of managing high solid MSW is crucial to retain its profound energy potential.

Stirring-based systems can be employed in MSW treatment anaerobic digesters to reduce solid deposition, which impedes microbial interaction with the waste substrate. To mitigate hazardous buildup, studies involving the use of hybrid reactor systems must be developed. Implementing circular economy principles and conducting life cycle evaluations are essential for commercial applications to quantify the economic and environmental implications of the treatment procedure.

8. CONCLUSION

Despite the potential of disposal and treatment processes, Indian municipalities continue to confront additional issues in MSW management due to massive garbage creation in relation to high population density. The majority of MSW management sites have observed proper processing, disposal, and energy generation. The purpose of the review was to describe various pretreatment and conversion options for municipal solid waste management. Biological techniques may be preferable in pretreatment procedures since they have no negative effects on the ecosystem. Chemical pretreatment has proven to be more successful in terms of efficacy. The role of thermal and biological processes is growing in MSW management when sustainable conversion strategies are employed. In terms of process efficiency, anaerobic digestion-based conversion is preferred. The commercial range of landfill and incineration, on the other hand, is largely appropriate for municipal treatment. Economic and environmental significance must be scalable prior to the introduction of sophisticated procedures. Therefore, for better municipal waste management, a limited group of private and public sector participants needs to be involved in reducing municipal waste and developing regulations to reduce pollution.

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NOMENCLATURE

MSW	Municipal Solid Waste
CPCB	Central Pollution Control Board
PAH	Polycyclic Aromatic Hydrocarbon
SSF	Simultaneous Saccharification and Fermentation
SHF	Simultaneous Hydrolysis and Fermentation
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
VFA	Volatile Fatty Acids
AD	Anaerobic Digestion

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